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Sandia National Laboratories

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To request additional copies or to subscribe, contact:
Michelle Fleming
Media Relations & Communications
Sandia National Laboratories
P.O. Box 5800, MS 1468
Albuquerque, NM 87185-1468
Voice: (505) 844-4902
Email: meflemi@sandia.gov

www.sandia.gov

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Credits:

CTO Office: Julia Phillips, Chris Miller

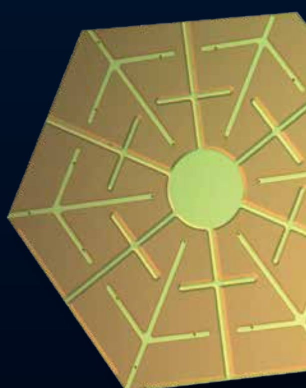
Media Relations & Communications
Manager: Jim Danneskiold

Editor:
Nancy Salem
(505) 844-2739, mnsalem@sandia.gov

Writing:
Neal Singer, Stephanie Hobby,
Sue Major Holmes, Nancy Salem

Photography:
Randy J. Montoya

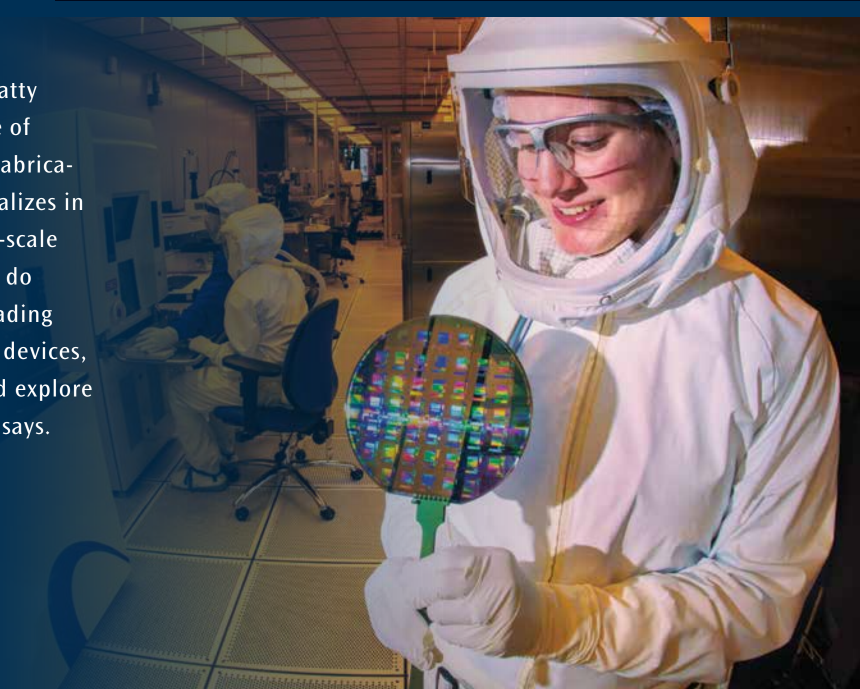
Design:
Michael Vittitow



ON THE COVER

Sandia microelectronics technician Patty Chenevey studies a wafer, a thin slice of semiconductor material used in the fabrication of microdevices. Chenevey specializes in microlithography. She patterns small-scale structures on a wafer. "I enjoy what I do because it allows me to work with leading researchers to fabricate cutting-edge devices, solve practical engineering issues and explore fundamental science questions," she says.

(Photo by Randy Montoya)



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Sandia RESEARCH

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MICROSYSTEMS play in the BIG LEAGUES

Think small. Really small. Our world at the micro- and nanoscale is a remarkable place that often operates outside the realm of classical physics. It is a world rich with wonder, possibility, discovery and potential.

Research into this tiny world at Sandia National Laboratories and other research institutions around the globe has accelerated dramatically over the past decade. Exciting discoveries are bringing about new technologies that significantly increase computer performance, create reliable, low-cost and more energy-efficient systems, produce new materials and devices that have higher performance or permit entirely new functionality, and enable ultra-portable, multifunction sensor systems that detect the slightest trace of chemical, biological or radioactive matter.

Sandia's Nanodevices and Microsystems Research Foundation is making significant progress toward increasing our understanding of physical phenomena from the nanoscale through the microscale. The foundation leverages Sandia's work in developing trusted radiation-hardened integrated circuits, its multidisciplinary microsystems capabilities and nanoscience device physics. Our multidisciplinary teams of scientists and engineers design and fabricate just about everything imaginable. That work has led to almost 300 patents and 43 R&D 100 Awards.

Critical to conducting this work is Sandia's Microsystems Engineering Sciences and Applications (MESA) Complex, a 400,000-square-foot facility designed to integrate the scientific disciplines needed to produce functional, robust and integrated microsystems. Sandia has a rich history of developing and fabricating semiconductors for mission applications within the National Nuclear Security Administration, NASA and other federal agencies, and for making significant contributions to industry.

This issue of Sandia Research has a number of articles that show how Sandia is moving ideas from concept to reality. You will also meet some of the nation's great scientists and engineers who are making that happen. You will see how Sandia is laying the groundwork for quantum computing through its work on three Laboratory Directed Research and Development (LDRD) Grand Challenges. You will also see how Sandia is exploring the rapidly evolving area of light-matter interactions and is working to develop neuro-inspired computers for a variety of applications, from tracking and sensing to detecting patterns or anomalies in large complex data sets. Sandia performs this work and much more with a variety of partners to fulfill our vital national security mission.

Gil Herrera
Director
Microsystems S&T & Components

MACRO MICRO NANO — oh my!

By Neal Singer

In physics, spatial scales run the gamut from what we can see to the infinitesimal.

Devices interacting at the micro- and nanoscales are showing signs they don't need the clumsy machinery of the macroworld to produce bounty.

Sandia manager Wahid Hermina sums up these phenomena in engineering terms: "We can leverage effects that occur only at those tiny scales [at dimensions 10 to 10,000 times smaller than the diameter of a human hair] to create smaller, lighter, more energy-efficient devices and systems with higher performance than traditional systems."

What's needed is to look at materials with new eyes. At the nanoscale, for example, materials subdivided into slivers aren't just smaller, they behave differently than the

Harnessing phenomena at the shortest lengths can yield devices with vastly better performance.

same substance at the macroscale, though conventional logic would say there's just less of it.

Consider solar panels. Photovoltaic bricks that make up the bulk of roof-top solar panels (as well as giant solar energy farms) are only 15 to 20 percent efficient. One reason is that silicon, the most commonly used brick material, doesn't efficiently convert the shorter blue and ultraviolet wavelengths of sunlight to electricity. Yet these wavelengths are more desirable to have in play because they offer more energy than those near the infrared, silicon's low-energy comfort zone. Faced with the panoply of wavelengths that constitute sunlight, silicon panels are like beggars with bad teeth at a steak banquet: They're limited to eating only the parsley.

This is because silicon bricks are restricted by what had been considered an immutable natural law: a material's "bandgap," the energy range between a material's valence and its conduction bands. Think of it as a catcher's mitt. The material can only "catch," or absorb, energy within that range. In silicon's case, it can absorb from UV photons only the same amount as from infrared photons. This leaves a lot of unused solar energy on the table as wasted heat.

Six-layer club sandwich

But, says Sandia researcher Greg Nielson, when silicon is sliced to slab thickness of 100 nanometers, an amazing thing happens: "The bandgap, once thought immutable, changes." So thinner slabs of silicon glued together can efficiently absorb a wider range of wavelengths than a single solid silicon slab of the same dimensions. Simply slicing at the nanoscale makes a more efficient macroscale brick.

More potently, a variety of photon absorbers can be created by layering very thin sheets of compound semiconductors. This technique uses combinations of gallium, arsenic, indium and other relevant elements known as III-V materials from their places in the periodic table. Various thin-sheet arrangements of these elements are formed with their atoms arranged similarly to the regular spacing of the junctions on a garden lattice. Each lattice contains a semiconductor with a different bandgap, making energy available for use from different wavelengths. By combining these into superlattice structures, one sheet above another, a solar panel can contain absorbers for a wide variety of wavelengths. Further variability can be achieved by altering each nanopanel's thickness, letting them absorb a still wider range of the sun's output. This combination of semiconductors can have more than double the bandgap of silicon, and though more expensive, is able to absorb and more efficiently convert light at blue and UV wavelengths as well as infrared.

"If we do it well," Nielson says, "we'll get a six-junction cell [visualize a six-layer club sandwich] with a theoretical efficiency of more than 60 percent. But if we just get over 50 percent, that would be terrific." The Sandia team has shown it can make three-junction cells, and has nearly completed a four-junction cell. "Solving this tricky bonding problem extends our reach on the high-energy side," Nielson says.

Because the lattices have different internal dimensions, Sandia researchers use a technique called 3-D integration to grow the layers on

Microelectronics process technician Loren Gastian looks into a wafer. Her work focuses on etching and cleaning the crystalline semiconductor material.

separate substrates. When mature, "a Sandia special sauce" (as Nielson puts it) permanently bonds them.

There's enough interest in the attempt to widen bandgaps and include more of them that NASA has scheduled some of Sandia's photovoltaic chips for a trip to the International Space Station, leaving them there a few years and testing their longevity after bringing them back.

The power of a photon

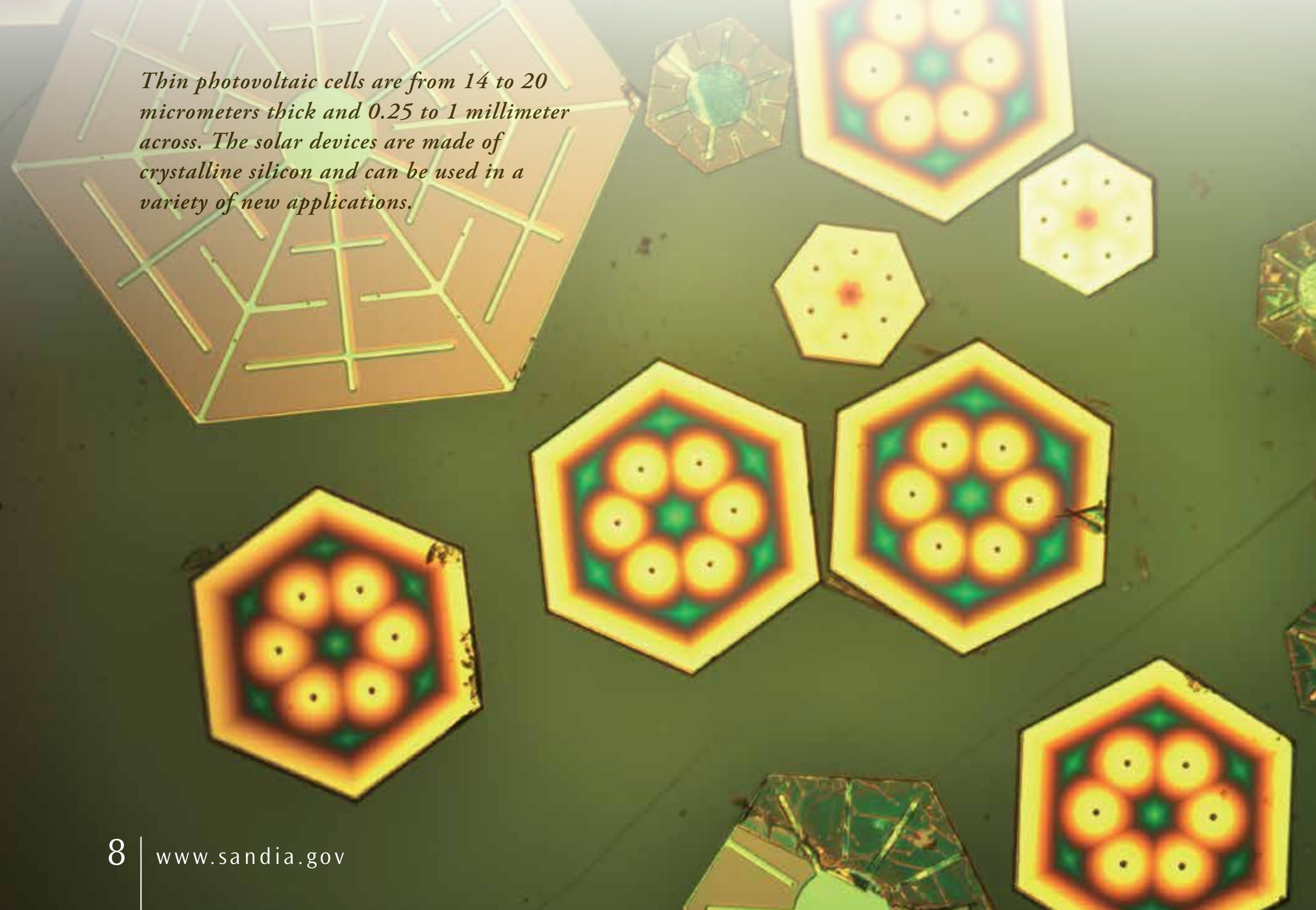
But there's more to working with light than converting it into electrical power. The nanoworld has other unique properties. It enhances interactions between light and matter because a photon's force, relative to structural forces, increases when confined to smaller volumes. So a single photon can have a big impact. New devices based on these phenomena make possible more compact systems for information processing. And because surface interactions dominate at these smaller scales, sensors and reactive catalysts also become more sensitive than at the macroscale.

So instead of looking at light as a tool by which our eyes see the world, consider visible light as researchers do, as electromagnetic waves that can be influenced and directed by other means than lenses, sunscreens and blackout curtains.

"Features of an artificial material built at scales much smaller than the wavelength of light can manipulate light in new ways," Hermina says.

Sandia researchers led by Igal Brener and Mike Sinclair, among others, have designed metamaterials — artificial electromagnetic structures at the micro- or nanoscale — that control light by virtue of their structure and shape.

Metamaterials created by arranging small structures of materials (metals or dielectrics) on a surface or in a volume can produce effects no earthly material can duplicate. They can bend light in ways that can make objects visible that otherwise would be too small for the magnification of the most finely crafted lens. Metamaterials also can bend light to make objects invisible at certain wavelengths, a spooky practice known as cloaking. Or they can black out an object at particular wavelengths. These techniques have achieved commercial acceptance in the microwave range. Sandia is helping lead the charge at infrared light wavelengths, a range of obvious interest to the military as well as the commercial world.



Thin photovoltaic cells are from 14 to 20 micrometers thick and 0.25 to 1 millimeter across. The solar devices are made of crystalline silicon and can be used in a variety of new applications.

MEET

Matt Eichenfield

Growing up in Las Vegas, Nev., Sandia physicist and Truman Fellow Matt Eichenfield was more interested in sports than studying. That changed during his junior year of high school when he took his first physics class. "I just loved understanding how things work in intricate detail," he says.

His doctoral dissertation was in the emerging field of nanotechnology where "unlike physics at larger scales, where you're stuck with the properties of the materials nature gives you, you can play with the geometry of materials at the scale of hundreds or thousands of atoms to make new materials with properties that do not exist in nature," he says.

Eichenfield's research used nanoscale structures to confine light and sound in unprecedentedly small volumes, up to 10,000 times smaller than the smallest human cell. The work earned him the Demetriades Prize for best Caltech thesis in the field of nanotechnology and was featured prominently in scientific news media. The discovery, Nature wrote, "could lead to ultra-sensitive biosensors … and provide an elegant cooling mechanism to help test quantum limits."

Eichenfield continues to explore light and sound at the nanoscale. A current project focuses on using nonlinear optical materials to create new laser sources.

And he didn't give up on sports. He runs half-marathons, snow skis and rides his mountain and road bikes thousands of miles a year.

STATS

- Bachelor of science in physics from the University of Nevada, Las Vegas.
- Master of science and Ph.D. in physics from the California Institute of Technology.
- Eichenfield is in the final year of a three-year Truman Fellowship, a highly competitive position at Sandia in which candidates are expected to have solved a major scientific or engineering problem or provided a new approach or insight in their thesis work.

Trapped in nanoscale cages

But metamaterials are not the end of the marvels in the nanorealm. There's also nano-optomechanics.

Nano-optomechanics, a new field of scientific research, involves trapping light in specially engineered nanoscale "cages." The photons behave very differently than those trapped in macroscopic structures. In particular, every photon exerts a very large force relative to the other forces at play.

That a tiny photon can exert force sounds odd, but this fact has been known to science a long time. Photonic force levitates objects in devices called optical tweezers, and the tails of sun-orbiting comets point away from the sun partly because of the forces photons exert. But these effects involve many photons. Nano-optomechanics confines photons in very small volumes, increasing the force relative to the surrounding mass so that a single photon can have a big impact.

"When a photon is trapped inside a material cage, it transfers part of its momentum every time it bounces off the walls," says Sandia Truman Fellow Matt Eichenfield. "The more times per second it transfers its momentum, the more force it exerts; so you want to make the thing holding it really small so it bounces off all the material's surfaces as often as possible."

Reducing the material to a nanostructure that contains only a few million atoms (a gram of material typically has about a million billion billion atoms), causes the photons to exert forces that become strong enough to shake the walls of the material.

"Every photon can exert a force on an appropriately engineered nanostructure equal to the weight of the structure that's confining it," Eichenfield says.

as soft as rubber or as hard as diamond. A bluer light makes it stiff, redder makes it flexible."

The same class of phenomenon that makes the photons exert large forces also allows the measurement of almost unimaginably small movements of the

Adam Rowen, foreground, and Christian Arrington work in a Sandia Surface Metal Micromachining lab. They specialize in LIGA, or lithography, electroplating and molding. Surface micromachining and electroplating at the microscale fill a gap between micromachining using conventional semiconductor processes and mesoscale machining using conventional machining processes.

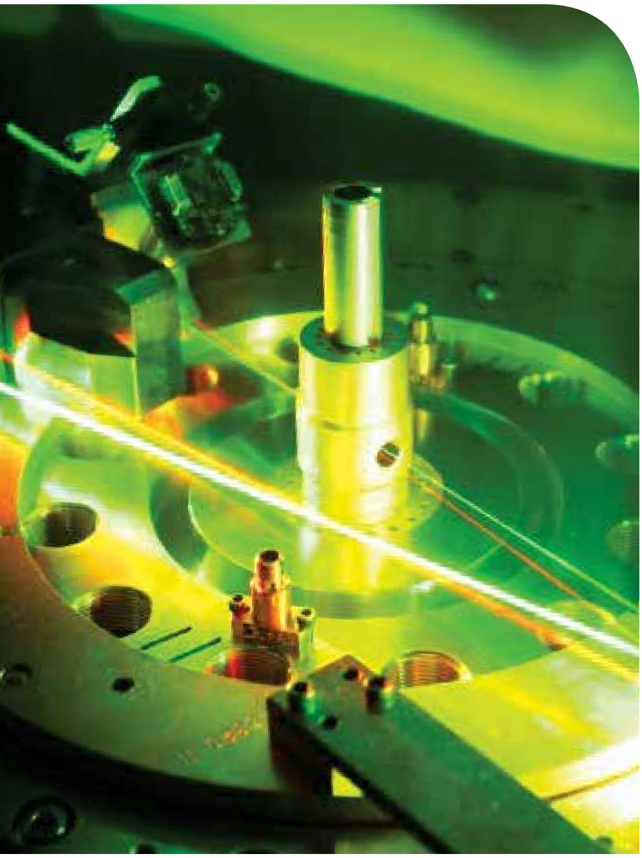
"If things worked like that in our macroworld, we would blow the walls out of our houses every time we turned on the lights."

The forces that photons exert at the nanoscale can even change the strength of the materials. "Take silicon nitride, a glass much stiffer than the silicon dioxide glass used to make everyday windows," Eichenfield says. "The color of light inserted in a specifically engineered silicon nitride nanostructure of less than 10 cubic microns totally determines the mechanical rigidity of the system, making the glass

cage walls to make exquisitely sensitive accelerometers, Eichenfield says.

"When you accelerate cages full of photons, the acceleration forces make the walls move, which causes the photons to leak out," he explains. "By measuring the light that spills out, we can detect the movement. It turns out that modern photon detectors are so good that we can detect movements hundreds of thousands of times smaller than an atom in this manner. We can use this to detect acceleration forces of an order a billionth the force of Earth's gravity."

Lasers align diagnostics and hardware prior to shooting on Sandia's Z machine, the world's most powerful and efficient laboratory radiation source.



Translating light-matter interactions

Other Sandia researchers are working on the materials border where photons and electrons interact. These efforts are creating active nanoplasmonic devices, which apply the benefits of the nanoscale to next-generation optical emitters, modulators and detectors.

Surface plasmons are groups of electrons oscillating together at a metal-semiconductor interface. Created by the interaction of electromagnetic waves (photons) with electrons in the material, plasmons are ideal intermediaries for translating light-matter interactions.

Historically, says Sandia optical engineer Gordon Keeler, most lasers and detectors have relied on semiconductors like silicon and gallium arsenide and dielectrics like glass to confine light and make useful devices. However, the so-called diffraction limit — the inability to bend light to focus it past a certain point — prevents these devices from getting particularly small. Traditional optoelectronic devices can only be shrunk to the micron size before their light begins to leak out. Metals were seen as merely adding unwanted loss to the system, something to be avoided whenever possible.

But, Keeler says, "if you add metals in the right way, you can minimize these losses and shrink light's footprint down." Adding metal in a plasmonic device can help confine light beyond the traditional diffraction limit and reduce such devices to the nanoscale. How? While light can be guided in semiconductors to make lasers and detectors, it also can be made to travel along metal surfaces as plasmons, which can turn sharper corners, fit in narrower gaps and interact more strongly with nearby matter.

The advantages of a smaller footprint are many: reduced size, higher speed and efficiency, lower power dissipation and greater sensitivity for the devices under investigation.

"We're using guided plasmons that only exist at the surface of a metal, where light can excite them," Keeler says. "They travel along the interface of the wires we lay down on a semiconductor. Plasmonic designs may be the foundation for new emitters and detectors, and represent a promising and potentially disruptive technology."

Workhorse lasers

No discussion of Sandia work at the nanoscale would be complete without mentioning VCSELs, or vertical cavity, surface-emitting lasers. These highly efficient, inexpensive workhorse lasers were aided in their development by decades of work at Sandia, says manager Charles Sullivan, and are used for a variety of applications like shrinking the size of atomic clocks and maintaining the accuracy of gyroscopes.

With a width measured in microns but a depth in nanometers, VCSEL layers are built up by accretion of III-V semiconductor materials with precision down to a single layer of atoms, says researcher Darwin Serkland. The desired laser wavelength is obtained by meticulously controlling the crystal growth process of the semiconductors, so that the thickness of each layer — of the hundreds that comprise the device — is accurate to within a single nanometer. ■

weirD SCIENCE

By Stephanie Hobby

Quantum is where things happen at Lilliputian scales. And some of it makes no sense, like the atom that moves when you look at it. But putting those strange laws of physics to work in bigger realms can revolutionize information technology.

Even Albert Einstein thought the whole idea was perplexing. The thought that a particle can be in two places at once, and that simply observing the particle has an effect on it, is just a little too far from rational thought. And yet, less than a century later, researchers say it's likely that the next generation of computers will rely on the downright outlandish rules of quantum mechanics.

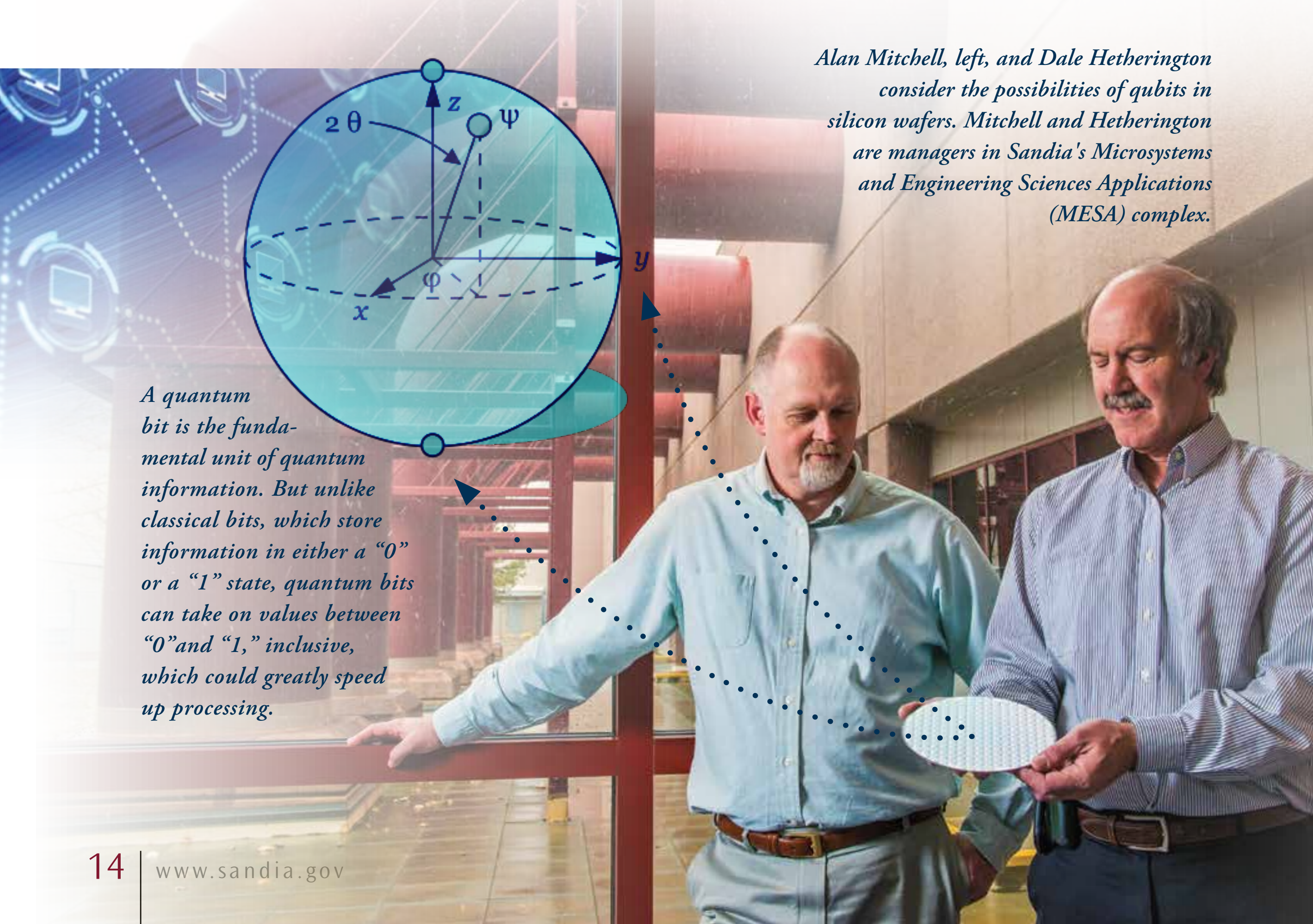
Sandia is moving the idea from concept to reality, using the peculiarities that govern the very small to build more powerful sensors, better atomic clocks and computers capable of solving problems conventional computers cannot.

Moore's Law, a concept described by Intel co-founder Gordon Moore in 1965, predicts that roughly every 18 months, the processing power of classical computers will double. But as devices shrink, they're running into fundamental physical limits, causing erratic behavior in transistors as electrons jump between circuits. Quantum computing is a promising and exciting way to extend performance beyond these limits.

Classical computers operate on the premise of switches — a string of bits that must be 1 or 0 — that are coded to produce data. The idea behind quantum computers is that you can take advantage of the particle's ability to be in two energy states at once, or both a 1 and a 0 — and everything in-between — simultaneously, so complex problems could be solved much faster.

The famous analogy is the traveling salesman who wants to cover a lot of ground efficiently. Using a classical computer, the salesman would have to plot out a variety of routes, one at a time, to figure out the fastest way between towns. A quantum computer, on the other hand, would use its basic information storage element, a qubit. Several qubits operating at once would be like swarms of salesmen covering the area, analyzing it and instantaneously delivering the most efficient route. And while that's an amazing concept, building such a device is exorbitantly difficult, and there's a lot of challenging work to be done.

Sandia researchers have been laying the groundwork for quantum computing for well over a decade. Three recent efforts were funded through Laboratory Directed Research and Development (LDRD) Grand Challenges to address major hurdles facing the field. In 2008, Sandia's LDRD program funded the three-year Quantum Information Science and Technology Grand Challenge to demonstrate hardware for a qubit in silicon. The challenge? Couple and manipulate qubits in the

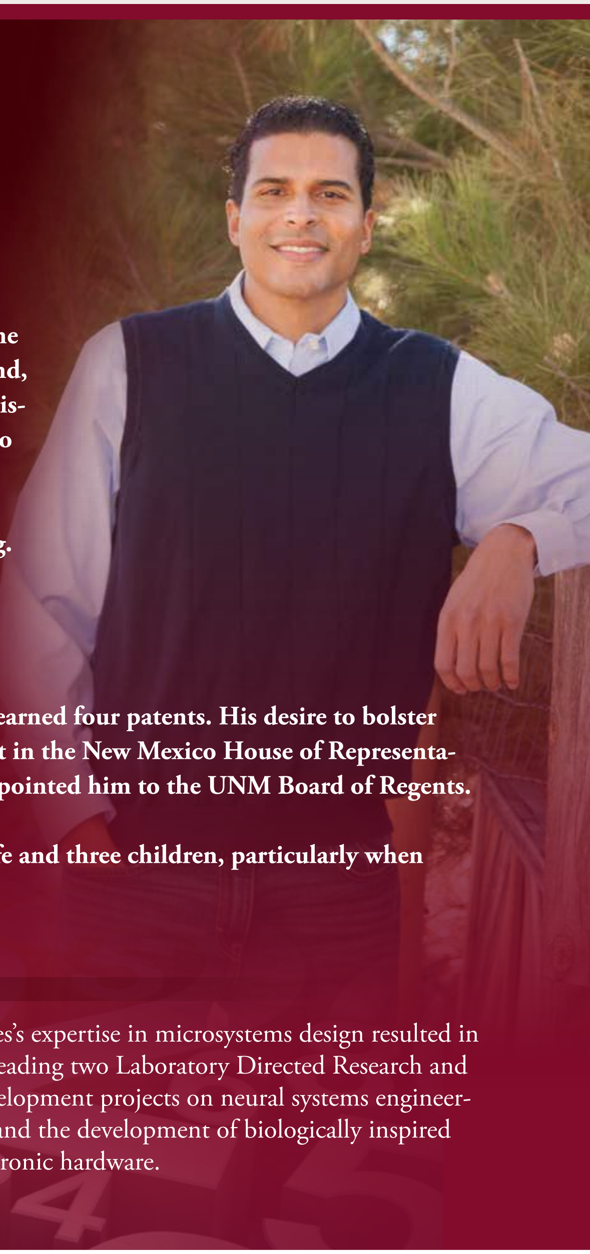


Alan Mitchell, left, and Dale Hetherington consider the possibilities of qubits in silicon wafers. Mitchell and Hetherington are managers in Sandia's Microsystems and Engineering Sciences Applications (MESA) complex.

A quantum bit is the fundamental unit of quantum information. But unlike classical bits, which store information in either a "0" or a "1" state, quantum bits can take on values between "0"and "1," inclusive, which could greatly speed up processing.

MEET

Conrad James



When Conrad James sees something that needs to be done, he does it. While that means the microsystems engineer, husband, father, University of New Mexico regent and former state legislator must make efficient use of every waking moment, it also creates a fulfilling and satisfying life.

Driving that lifestyle is a passion for science and engineering. "I have an innate curiosity to know how the world works," he says. James learned about Sandia while attending technical conferences as a grad student. Hired in 2002, he quickly immersed himself in research and publishing. James has co-authored papers in dozens of technical publications and earned four patents. His desire to bolster science and engineering education inspired him to win a seat in the New Mexico House of Representatives in 2011-12. In January 2013, Gov. Susana Martinez appointed him to the UNM Board of Regents.

When not working, James enjoys spending time with his wife and three children, particularly when he gets to cheer them on at their weekend sporting events.

STATS

- Bachelor of science in electrical engineering from the University of Notre Dame.
- Master of science and Ph.D. in applied and engineering physics from Cornell University.
- James's expertise in microsystems design resulted in his leading two Laboratory Directed Research and Development projects on neural systems engineering and the development of biologically inspired electronic hardware.

form of a quantum circuit that produces a useful function. Essentially, isolate a single electron, put it in a spin state, bring another one nearby to have them interact with each other, and then pull them apart again. With the right combinations, you can do a mathematical calculation. But you have to isolate and control that single particle first.

"A lot of our research is centered on how to isolate, capture, hold and manipulate a single electron, ion or neutral atom," says Sandia senior manager Andy Boye. "We're now to the point where we can capture and hold individual particles and look at those energy structures and see how they vary in certain conditions."

Sandia's AQUARIUS Grand Challenge was next, focused on developing a quantum-computing architecture based on adiabatic physics. A primary roadblock to quantum computing is the exceptional noise sensitivity of qubits — the electron or ion must be isolated and controllable at the same time — so the goal of AQUARIUS was to keep a quantum computer in its lowest-energy configuration, thus reducing the impacts of noise. "For quantum information processing systems, it's all about how the energy of the system propagates," Boye says. "In the case of adiabatic quantum computing, we try to stay in the lower energy states of the system and do things slowly enough that you don't jump out of those lower energy states. If you define the system correctly, then you can propagate through the system and at the end of the calculation, you'll have the right answer."

The third Grand Challenge, Sandia Communications and Authentication Network using Quantum Key Distribution, or SECANT QKD, started last fall and is seeking ways to do ultra-secure communication with applications in energy, cybersecurity, defense and more. “You could say we’re making a flying qubit,” says Sandia manager Dan Barton. “With other technology, the qubit physically stays on the device you’ve made. A flying qubit means we take a photon — a particle of light — put some quantum information on it, and send it 100 kilometers through free space or fiber optics. We’re looking at communicating information securely using single photons.” SECANT is expected to address the serious need for tighter cybersecurity. With Quantum Key Distribution, two people can communicate securely using encryption keys without having to physically exchange the keys.

The Grand Challenges and microfabrication and nanoscience facilities have helped cement Sandia’s position as the place with unique capabilities in the quantum information sciences world. By taking advantage of onsite microfabrication capabilities, Sandia researchers are developing and fabricating ion traps used in research around the world. Sandia can build arrays of ion traps to store many single ions and move them around the chip where they can run a quantum algorithm. “We are recognized for having capabilities that in turn benefit the international community and advance the science,” Boye says.

The research program has led to other interesting developments. Scientists have built a magneto-encephalographic (MEG) sensor that responds to extremely small changes in magnetic fields in the human brain. An exciting aspect is that Sandia designed the sensors to operate at room temperature, which would dramatically reduce costs. The current state-of-the-art requires sensors to be cooled to liquid helium temperatures, a chilly minus 452.11 degrees Fahrenheit.

Sandia’s Quantum Information Science (QIS) teams are making remarkable progress in advancing this science, and in coming years researchers plan to study new ways to use few qubit quantum devices for enhanced sensing, to generate and quantify random numbers, to build low-noise electronic devices and cultivate new ideas for optical manipulation. Boye smiles at the thought of addressing future challenges. “Put simply, we want to understand what’s possible and then demonstrate it.” ■

what’s next

YOU CAN HEAR ME NOW

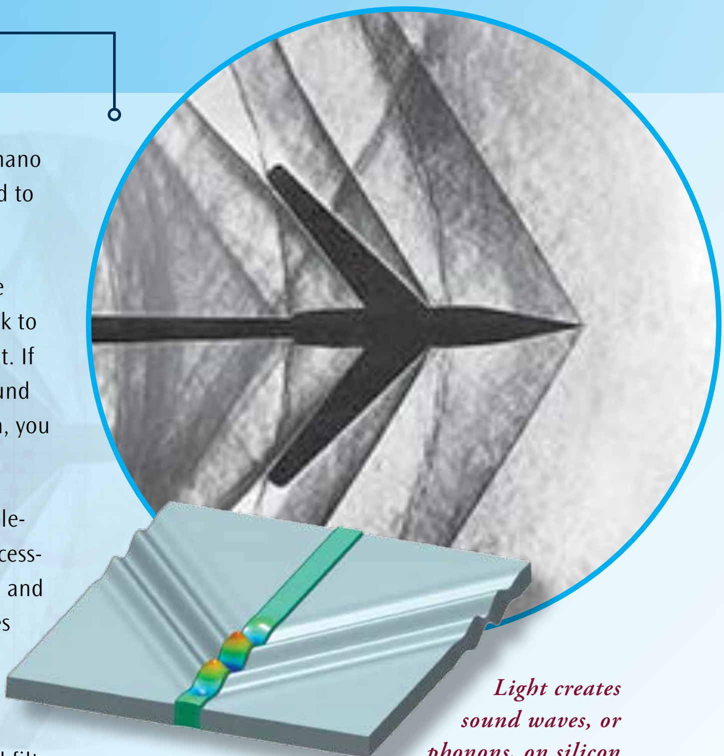
By Nancy Salem

Sometimes in communications slower is better. A signal can be lost in a fast-moving field of many signals but heard at a less hurried pace.

The conventional way to delay a light wave is to send it on a detour through a spool of fiber a kilometer long. Sandia Labs is looking smaller, to delay a signal in the space of a millimeter.

“By creating a delay, you can do signal processing not otherwise possible,” says Patrick Chu, manager of Sandia’s Applied Photonic Microsystems Department. “We use a nano application to achieve something you normally have to do in very large bulk materials.”

Chu’s group is studying nano-optomechanics, the mechanical force generated when light interacts with matter, and phononics, the transformation of that force into sound waves, or phonons.



Light creates sound waves, or phonons, on silicon membranes engineered to generate mechanical force, much like an airplane forms mach waves in flight.

The change happens as light is sent through a nano waveguide onto a silicon membrane engineered to generate mechanical force and phonons.

"What's really neat is if you design the structure appropriately you can convert the phonons back to light," Chu says. "Sound travels slower than light. If you have a signal in light form, put it in the sound domain and convert it back to the light domain, you can create a delay in the signal."

Researchers are developing a chip-scale delay element that could one day be used for signal processing in advanced government and military radio and radar communications. Chu offers two examples — noise and distortion. "As radio signals come into receivers, you want to be able to listen to many channels at the same time. One way is to convert the radio wave into sound waves and filter out the noise so you can better hear the signals you care about," he says. "And in a phased-array radar system a signal won't be heard by the antenna if it is not phased correctly. If you can make a delay element to tune the signal you can hear it and block out others."

Phonons also transmit heat and the team is developing structures to block and redirect it. Heat-steering materials could have tremendous impact on the electronics industry by keeping microprocessors from overheating. "The challenge is to get heat away from sensitive electronics, such as the processors on military airplanes, so they won't fail," Chu says. "Advanced heat management may improve the reliability and durability of electronics."

Heat and sound on a membrane are manipulated with phononic crystals, small holes in the material that allow the energy to propagate, be trapped or bounce back. "We can manipulate the phonons with the crystals and channel the energy in different ways," Chu says.

In practice, a single waveguide sits on a membrane and light travels through it, creating acoustic vibrations. Phononic crystals manipulate the wave and make it transmit more easily, or let it be blocked or steered. A next step is to assemble multiple waveguides, setting up the delay element in which phonons are converted back to photons and again to phonons. "The waveguides are small, with thickness in the order of a thousandth of the diameter of a human hair," Chu says. "The alternative is to have waveguides that run around a big spool and have the same kind of delay effect."

The project was started three years ago at Sandia by Peter Rakich, now a professor at Yale University, a Sandia partner in the work along with Zheng Wang at the University of Texas at Austin. The Sandia project lead is Jonathan Cox.

"Filtering and processing radio frequency signals with light and sound at the nanoscale has opened up a new paradigm for radio electronics," Cox says. "And I think there is a good deal of unrealized potential yet to harvest." ■

Can you visualize a billionth of a second?

Tiny fractions of time can make a difference in everything from global positioning to video streaming. A new generation of clocks using lasers and energy at the atomic level offers mind-boggling accuracy in an ever smaller package.

:00:00:01

By Neal Singer

Just as carpenters cut wood, engineers and scientists divide time. Establishing time is useful, in ascending order of precision, when two friends meet for lunch, a general wants the prongs of his attack to proceed exactly as planned or when global positioning satellites use milliseconds to locate objects and travel paths anywhere in the world.

The last case, and others equally arcane, led Sandia researchers to help create a handheld atomic clock called CSAC (chip-scale atomic clock) available for military and commercial use. They are now attempting a second, still finer instrument called IMPACT (integrated micro-primary atomic clock technology). Either may eventually help tune what is expected to be an extremely accurate and compact gyroscope (PASCAL) to improve the ability of ships, airplanes and rockets to stay on course. The three devices use lasers and energy emissions at the atomic level to determine time with accuracies to millionths and even billionths of a second.

The projects have been funded by the Defense Advanced Research Projects Agency (DARPA).

CSAC—a matchbook-sized atomic clock 100 times smaller than its commercial predecessors—was created by Symmetricom Inc. (purchased by Microsemi Corp. in 2013) in coordination with MIT's Draper Laboratory and Sandia researchers. At about 1.5 inches on a side and less than a half-inch in depth, it is not only portable but needs 100 times less power than its predecessors. Instead of 10 watts, it uses only 100 milliwatts.

Atoms and lasers

Much of that reduction was credited to a tiny laser, called a VCSEL, introduced by Sandia. The result? "It's the difference between lugging around a device powered by a car battery and one powered by two AA batteries," says lead investigator Darwin Serkland. Where an old-fashioned alarm clock uses a spring-powered series of gears to tick off seconds, a CSAC counts the frequency of electromagnetic waves emitted by cesium atoms struck by a VCSEL beam to determine the passage of time.

The clock's uses are specialized. Miners far underground or divers engaged in deep-sea explorations, blocked by natural barriers from GPS signals, could plan precise operations with remote colleagues who also had atomic clocks, because their timing would deviate from each other by less than one millionth of a second in a day. The

Optical engineer Darwin Serkland measures the wavelength of a tiny laser called a VCSEL, or vertical-cavity surface-emitting laser. The monitor image shows a bright circle of light from a VCSEL operating at the 894 nanometers wavelength needed to drive the atomic clock.

clock can also help keep information packets travelling by different routes to the same destination in temporal order.

The clock's many uses, both military and commercial, are why DARPA funded the work from 2001 until the CSAC hit the commercial market in 2011.The success of the tiny machine led DARPA to fund development of a clock a thousand times more accurate with improved long-term stability of the timing signal using trapped ytterbium ions to keep its output accurate.

Engineering grit needed

Still in the experimental stage, IMPACT is "currently the size of a goose egg, and with prospects for further miniaturization," says Sandia principal investigator Peter Schwindt, who has worked on the project five years.

In the second-generation atomic clock, a tiny, cigar-shaped gaseous bundle of ytterbium-171 ions is used as a reference to fine-tune and stabilize the frequency emitted by a voltage-tuned quartz oscillator, which has a 10 megahertz output frequency that can be divided down to emit exactly one pulse per second.

Making sure that output is accurate takes engineering grit. The fine-tuning procedure uses internal clock electronics to translate the 10 MHz quartz output into a 12.6 GHz microwave signal that is applied to the caged ytterbium ions. The ions have two hyperfine ground states. The split-level states are separated by an energy corresponding to 12.6 GHz and initially exist only in their lower, less energetic split state. A certain number will absorb the 12.6 GHz microwave photons and transition to the higher ground state.

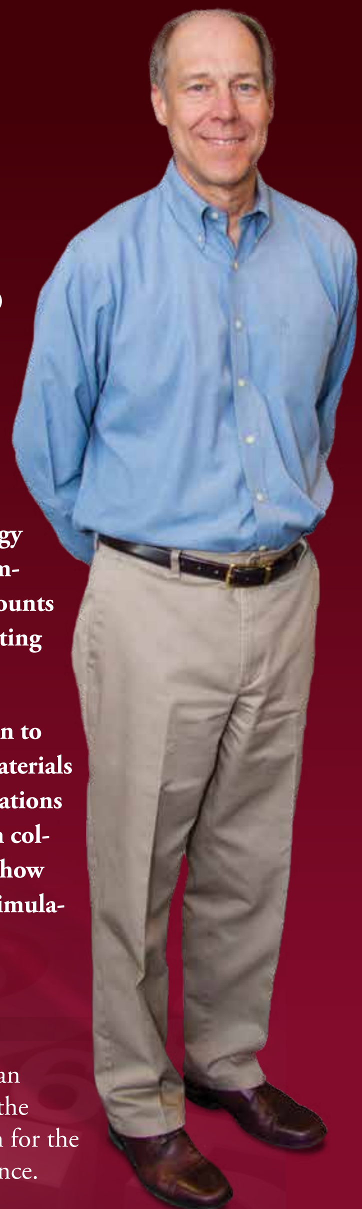
The number of ions that transition depends on the accuracy of the microwave frequency. When exactly at 12.6 GHz, many ions will absorb energy and jump to the higher state; if the signal has strayed, few will be able to. The result is then read by applying two lasers that further energize the ions, creating measurable fluorescence. Dim results are improved by using electronic feedback to correct the microwave signal. The same correction resets the quartz signal.

Either of these clocks could be used to aid PASCAL (Primary and Secondary Calibration on Active Layer), a micro-electromechanical system (MEMS) just getting off the ground in one of Sandia's micromachine groups. The device consists of an arm with a weight driven back and forth like a brick on the end of a spring. When the sensor rotates, it moves a little side to side due to the Coriolis force, allowing the device to detect the rotation rate.

"What we're doing differently from other labs on this project is that rather than reading the angle out with capacitors, we're using an optical sensor, i.e., a laser," Serkland says. "We believe it could have better performance than the electrical readout version, but

MEET

Mike Coltrin



Coltrin is an avid hiker who tries to get outdoors every weekend. In 2005 he wrote the popular *Sandia Mountain Hiking Guide*, describing about 60 trails in the mountains east of Albuquerque. "I especially enjoyed making GPS tracks and maps of all the trails in putting together the book," he says. His 30-year hobby has taken him to beautiful places around the world, including Patagonia, the Alps and the top of Mount Kilimanjaro.

Coltrin is director of the Energy Frontier Research Center for Solid-State Lighting Science funded by the Department of Energy's Office of Basic Energy Science. Sandia is the center's lead laboratory. "The goal of our center is to improve energy efficiency in the way we light our homes and offices, which accounts for 20 percent of the nation's electrical energy use," he says. "Solid-state lighting has the potential to cut that energy consumption in half, or even more."

For most of his 34-year career at Sandia, he has done modeling and simulation to understand the chemistry that occurs during the growth of semiconductor materials like silicon, gallium arsenide, diamond and nitride materials that have applications to solid-state lighting. "A highlight for me has been working very closely with colleagues doing the actual growth experiments in the lab to jointly understand how these very complex processes work," he says. "I think the close ties between simulation and experiment are a distinguishing strength at Sandia."

STATS

- Bachelor of science in chemistry from Oklahoma State University.
- Master of science and Ph.D. in chemistry from University of Illinois at Urbana-Champaign.
- Fellow of the American Physical Society and the American Association for the Advancement of Science.

at present, it's just a nice design. In a year we'll know if our design pans out."

Calibrated in the field

An atomic clock and an optically read gyroscope in a navigational system not only provide higher resolution but also immunity from noise issues that affect electrostatic sensing. A VCSEL light source—the same as used for the atomic clocks—provides a miniature light source important for low weight, and sufficient power and performance.

PASCAL project lead Murat Okandan says that other microscale gyroscopes drift significantly after their initial calibration, but PASCAL will be able to be calibrated in the field without any loss of sensitivity. "The atomic clock provides a precision time source," he says. "For calibration, you need a reference point, and one of the key factors is time."

Phase 1 of the project, now completed, included layout and testing of an electrostatic read-out version, "demonstrating some of the design characteristics and critical mechanical features and allowed us to consider optical detection of displacements," Okandan says.

Phase 2, now under way, uses lasers to achieve the desired detection and calibration functions. Fabrication of parts will continue through 2014. The plan is to have assembled sensor measurements beginning in the fourth quarter of 2014 and continue into 2015. ■

By Sue Major Holmes

COMMON SENSE COMPUTER PURSUES THE ESSENCE OF THOUGHT

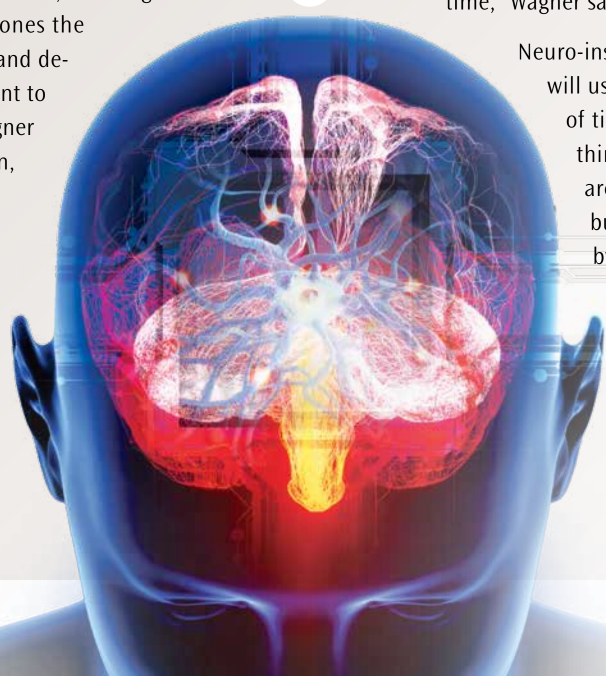
Our brain is incredibly well suited to handling whatever comes along, plus it's tough and takes very little energy to operate. Those attributes are precisely what's needed for neuro-inspired computing.

"Today's computers are wonderful at book-keeping and solving scientific problems that use partial differential equations, but they're horrible at just using common sense, seeing new patterns, making decisions," says Sandia cognitive sciences manager John Wagner.

So researchers turned to the brain as "the proof that you can have a formidable computer that operates on the power of a 20-watt light bulb and lasts a hundred years," Wagner says.

Neuro-inspired computers would be ideal to control autonomous systems such as unmanned aerial vehicles or sensors, solve big data problems like the ones the cyber world faces, and detect patterns or point to anomalies, say Wagner and Murat Okandan, a microsystems researcher.

"If you do conventional computing, you are doing exact computations, and exact computations only.



If you're looking at neuro computation, you are looking at history, memories and your sort of innate way of looking at all that, then making predictions about what's going to happen next," Okandan says. "That's a very different realm."

Modern computers are largely calculating machines with a central processing unit and memory that stores a program and data. They take a command from the program and data from the memory to execute the command, one step at a time, despite how fast they might operate.

The architecture of neuro-inspired computers will be radically different, combining the functions into a network so processing and storage live together, Wagner and Okandan say. "It won't be a serial step-by-step process; it'll be this network processing everything all at the same time," Wagner says.

Neuro-inspired computers will use the critical notion of time inherently. "The things that you represent are not just static shots, but they are preceded by something and there's something that comes after them" to link what happens when. This demands massive interconnectivity and a unique way of encoding information in the activity of the machine structure itself, Okandan says.

Each neuron in a neural structure connects to 10,000 neurons, which in turn connect to 10,000 other neurons in a dynamic way. Conventional computer transistors, on the other hand, connect at most to four other transistors in a static pattern.

"So they're very different in terms of how things are connected, how they function. The devices and chips and the architecture we're contemplating are going to enable that kind of interconnectivity," Okandan says. "The substrate regulates and updates itself by internal rules, locally performed functions, rather than an external program driving updates to the network."

Computer design has drawn from neuroscience before, but a recent explosion in brain research opens more possibilities. While it's far from a complete picture, "it's a lot more guidance in terms of how neural systems might be representing data and processing information," and offers clues about replicating those tasks in a different structure to address problems that are impossible with current computing and control systems, Okandan says.

He estimates a brain-inspired computing project could develop early examples of new architecture in the first several years, while higher levels of complexity could take decades.

"The ultimate question is, 'What are the physical things in the biological system that let you think and act, what's the core essence of intelligence and thought?' That might take just a bit longer," he says. ■

MEET

Mary Crawford

Crawford, a senior scientist in Sandia's semiconductor material and device sciences department, has an interest in optics that goes well beyond the laser lab. "I have always been fascinated by colors and patterns and have collected kaleidoscopes for many years. Far from being simple toys, many handcrafted kaleidoscopes are true works of art."

Most of her career has focused on getting semiconductor materials to emit light more efficiently to spur major technology advances. Her Sandia team has performed fundamental research for more than 15 years on materials used in LED-based lighting, a more energy-efficient technology than incandescent lamps. Her work also has helped extend semiconductor light-emitting devices into the deep ultraviolet for such uses as water purification, material processing and fluorescence-based sensing of bioagents.

In 2000, Crawford took entrepreneurial leave from Sandia to join a Tampa, Fla., startup company, Uniroyal Optoelectronics, to develop LEDs for solid-state lighting and other applications. "It was extremely rewarding to work with such a close-knit team and to feel like we were building something from the ground up. I ultimately returned to Sandia but that experience gave me new technical skills and a valuable perspective on research in an industrial setting."

STATS

- Bachelor of arts in physics from Holy Cross College, Worcester, Mass.
- Master of science and Ph.D. in physics from Brown University, Providence, R.I.
- Crawford began her Sandia career as a postdoctoral appointee in 1993 and joined the staff in 1994.
- She has co-authored more than 100 journal articles and holds five patents.

Sandia RESEARCH

Media Relations & Communications
Sandia National Laboratories
P.O. Box 5800, MS 1468
Albuquerque, NM 87185-1468

LOOKING BACK

Sandia technology went to the moon and found water.

Optical know-how developed at the labs in the 1990s rode aboard NASA's 2009 Lunar Crater Observation and Sensing Spacecraft (LCROSS) whose primary quest was water. The mission deliberately crashed a rocket stage, kicking up a plume of moondust that was analyzed by spectroscopic instruments on the spacecraft, including some commercialized by a company founded by Sandians.

The two near-infrared spectrometers looked at reflected sunlight from the lunar debris and verified the presence of water.

The polychromator technology was recognized as one of Industry Week magazine's Top 25 Technologies of 1999 and won the 2000 Lockheed Martin Nova Award.

The spectrometers used a MEMS-based (micro-electromechanical systems) diffractive optical component developed by Sandia, MIT and Honeywell. Michael Sinclair, Mike Butler and Tony Ricco of Sandia and Stephen Senturia of MIT were the original inventors, with two seminal patents.

Funding came from the Department of Energy's environmental management and environmental restoration programs. The project morphed in 1997 into a larger effort funded by the Defense Advanced Research Projects Agency (DARPA). Sandians Kent Pfeifer and Bill Sweatt joined the team and, in late 2000, Sweatt, Butler and Sinclair started Polychromix of Woburn, Mass.

Thermo Fisher Scientific, which bought Polychromix, markets instruments using the technology to, among other things, analyze what types of plastics recycled material may contain.

But its claim to fame lies more than 250,000 miles away. "It picked up the first definitive signals of water on the moon," Sinclair says.

— Sue Major Holmes

The polychrometer was designed for remote sensing and rapid identification of chemicals under battlefield conditions. Its uses expanded and the technology was used to find water on the moon.